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# AERODYNAMIC CHARACTERISTICS OF AUTOMOBILE MODELS

By R. H. Heald

ABSTRACT

In the investigations described in this paper the drag coefficients were found to vary from 0.0018 lb./ft.$^2$/m.p.h.$^2$ for the model representing an automobile of 10 years ago to 0.0014 for the model representing an automobile of the present. Elimination of the fenders and other projections together with pronounced fairing of the body of one model reduced the drag coefficient to 0.0006. Lateral and longitudinal forces were also measured. The lateral force was found to vary approximately as the angle of the relative wind if this was less than 20° to the direction of motion of the automobile. Very little variation in longitudinal force coefficient was observed with this range of angles.

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## I. INTRODUCTION

In view of the possibility of obtaining improved fuel economy or higher speeds by streamlining an automobile body and the consequent trend of design in this direction, it has appeared desirable to assemble the results of wind-tunnel tests made at the Bureau of Standards. The relative values of the drag coefficients serve to give an approximate indication of the progress achieved in reducing the air resistance of the automobile body during the past 10 years.[1]

The tests were routine in character and because of limited time no attempt was made to extend them for the purpose of determining the "best" shape. In all cases the measurements were made by the suspension method, the models being swung from light steel wires secured to the roof of the wind tunnel. The wind blowing on the model caused it to deflect a distance which was measured. The total drag corresponding to a given wind speed was computed from the weight of the model and the deflection, a correction being applied for the drag

[1] Some of the more recent tests and discussions relating to the aerodynamics of automobile bodies are given in the following publications:
Agg, T. R., and others, Bull. Iowa State College, nos. 67, 88.
Andrade, Julio, J.Soc.Auto.Engrs., vol. 29, p. 29, 1931.
Burney, Sir Denistoun, J.Soc.Auto.Engrs., vol. 30, p. 57, 1932.
Conrad, L. E., Public Roads, vol. 6, no. 9, p. 203.
Fishleigh, W. T., J.Soc.Auto.Engrs., vol. 29, p. 353, 1931.
Heldt, P. M., Auto. Ind., p. 368, Mar. 25, 1933.
Lay, W. E., Proc. Highway Res. Bd., vol. 11, pt. 1, p. 36, 1932.
Lay, W. E., J.Soc.Auto.Engrs., p. 144, April 1933.
Lay, W. E., J.Soc.Auto.Engrs., p. 177, May 1933.
Marti, O. K., Trans. Soc. Auto. Engrs., vol. 26, p. 333, 1931.
Pawlowski, F. W., Trans. Soc. Auto. Engrs., vol. 27, p. 5, 1931.

of the supporting wires. The effect of the ground was represented by testing the models near a large platform, the plane of which was parallel to the axis of the tunnel.

The "head-on" resistances of the models are expressed in the form of coefficients, where:

$$K=\frac{R}{AV^2}$$

$R$ = resistance in pounds.
$A$ = projected frontal area in square feet.
$V$ = air speed in miles per hour.

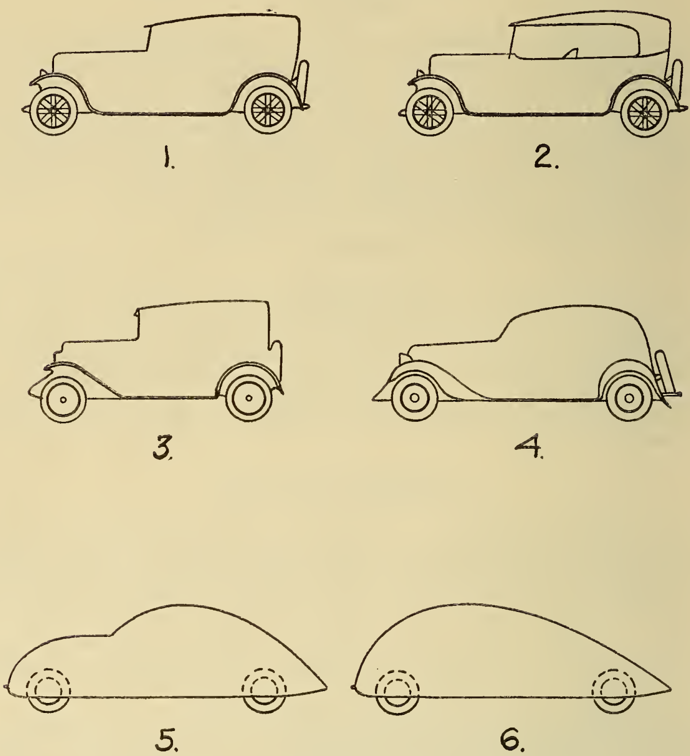



FIGURE 1.—*Outline drawings of the models.*

Some of the tests were devoted to determining the effect of the wind blowing on the model from an angle.

## II. THE MODELS

*First series.*—Models 1 and 2 (fig. 1) represented cars of the heavier class built about 1922. These models were to one quarter scale and were constructed of metal with considerable attention to detail. Model 1 represented a sedan; model 2, a touring car. Both models were provided with wire wheels. They were furnished by the manufacturer of the full-scale car.

*Second series.*—Model 3 (fig. 1) represented the lighter type of sedan produced about 1928, to one eighth scale. Its general outline was similar to that of model 1. The body proper was constructed of wood.

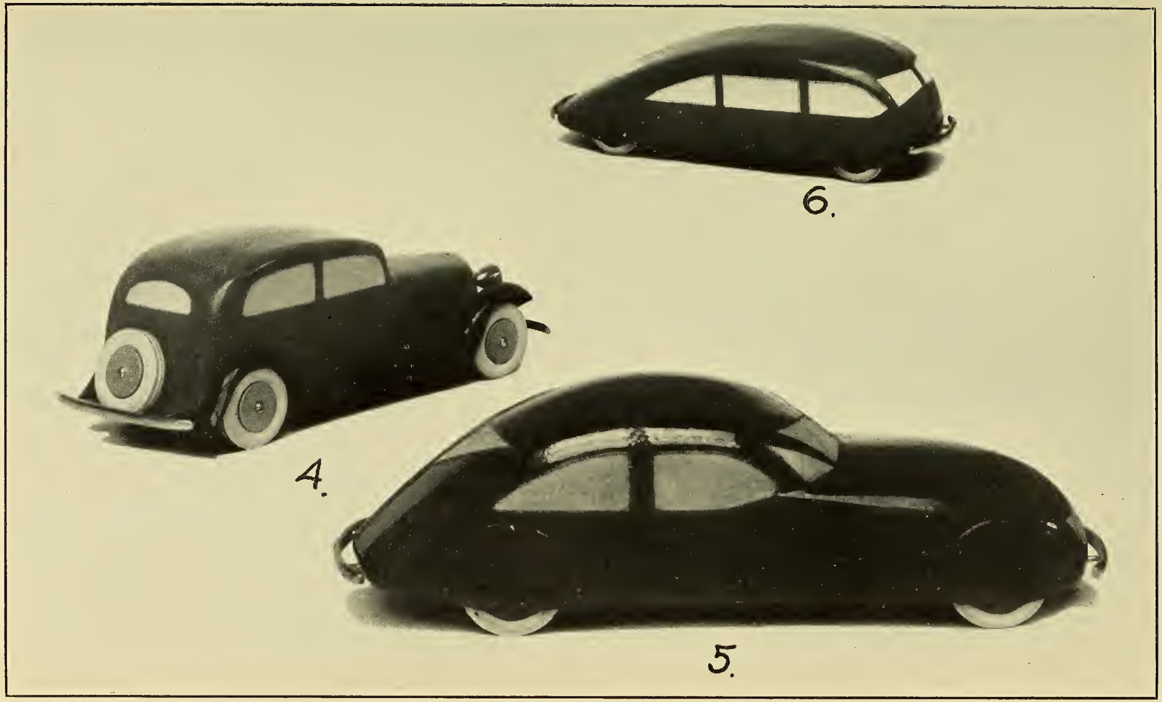



FIGURE 2.—*Views of models 4, 5, and 6.*

The one-fifteenth scale models were of the same projected frontal area.

The fenders, apron, headlights, and wheel disks were made of metal. Windows were represented by recesses cut into the body.

A duplicate of model 3 was furnished by the manufacturer in order that some tests might be made using the method of images. In this method one model was inverted and suspended below the other, wheel to wheel, and the resistance of the pair was determined. The resistance of one model was taken as one half the corrected resistance of the pair. This method assumes from theory that the conditions of air flow between the two models simulate the conditions when the full-scale car is moving along the road. The results of the tests by the image method differed from those by the platform method by about 2 percent.

*Third series.*—Models 4, 5, and 6 (figs. 1 and 2) were constructed principally of wood. Model 4 represented a composite 1933 sedan. It was fitted with exposed fenders, bumpers, headlights, and spare tire. The wheels were of the disk type. Model 5 was more thoroughly streamlined, the wheels being enclosed in the body. The bumpers were the only projecting members. The windshield was inclined 45° to the vertical and was faired smoothly into the engine hood and the top of the model, which was rounded both front and rear. In the case of model 6 the whole upper surface was faired smooth and the wheels were enclosed in the body. Its contour resembled that of an airfoil with flat lower surface. The scale of models 4, 5, and 6 was one fifteenth.

## III. RESULTS OF THE DRAG TESTS

The results of the drag tests are given in table 1. It will be noted that the drag coefficients for models 1 and 3 differ by only a few percent, although the sedans which they represent were built at times separated by an interval of 6 years. Model 4 representing a sedan built 6 years later than the one represented by model 3, and having a somewhat smoother outline, gave a coefficient about 25 percent less.

The greatest reduction in air resistance was accomplished by eliminating the fenders and other projecting members which give rise to turbulent air flow and by fairing the top as in the case of model 5. The value of $K$ found for this model was of the order of 70 percent less than the value of $K$ for models 1 and 3. An additional slight decrease in the value of $K$ was obtained by eliminating the windshield and fairing the whole body of the car so as to resemble a thick airplane wing section (model 6).

TABLE 1.—*Values of K*

| Model no. | Description | Model area | Test speed range | $K$ |
|---|---|---|---|---|
| | | *Sq. ft.* | *M.p.h.* | |
| 1 | 1922 sedan | 1.77 | 13–60 | 0.0017 |
| 2 | 1922 touring car | 1.87 | 13–60 | .0019 |
| 3 | 1928 sedan | .393 | 14–70 | .0018 |
| 4 | 1933 sedan | .098 | 30–70 | .0014 |
| 5 | Streamline sedan | .098 | 30–70 | .0006 |
| 6 | do | .098 | 30–70 | .0005 |

## IV. EFFECT OF SIDE WINDS

The action of the aerodynamic forces on an automobile driven in a side wind differs materially from the action of the forces when it is driven through still air or against a head-on wind. In figure 3 the vector $V_A$ represents the relative velocity and direction of the air with respect to the car when the car is moving through still air or against a head-on

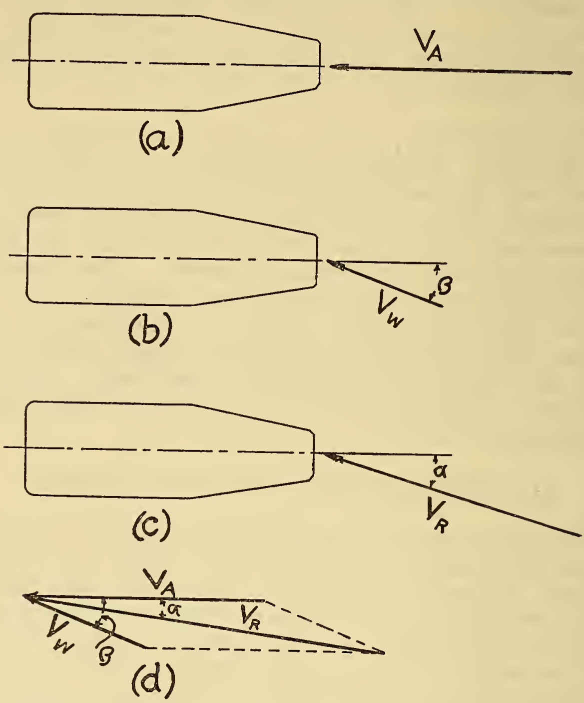



FIGURE 3.—*Diagrams illustrating the composition of wind and automobile velocities.*

$V_W$=wind velocity with respect to ground.
$V_A$=automobile velocity in still air.
$\alpha$=angle of relative wind, $\beta$=angle of natural wind; both are with respect to the longitudinal axis of the automobile.

wind. The effect is assumed here to be the same when the automobile is stationary and the wind blows head-on against it.[2] Figure 3 (*b*) with vector $V_W$ represents the condition when a natural horizontal wind blows on the stationary automobile at an angle to its longitudinal axis. When these two winds occur simultaneously they give rise to the condition represented in figure 3 (*c*) in which the two vectors are replaced by the resultant, $V_R$. The graphical solution is obtained by drawing the vectors and completing the parallelogram as indicated in figure 3 (*d*). The solution may also be obtained arithmetically by means of the formulas:

[2] The only reason for a difference lies in the method of representing the aerodynamic effect of the motion of the automobile over the road, the so-called "ground effect." The correct representation of this condition in the wind tunnel involves the use of a rather wide belt moving just beneath the wheels of the model and having the speed and direction of the air stream. The difficulty of maintaining proper adjustment of the belt for high lineal speeds where clearances are small is apparent, and accordingly this method of representing the ground effect has not been used in wind tunnel tests.

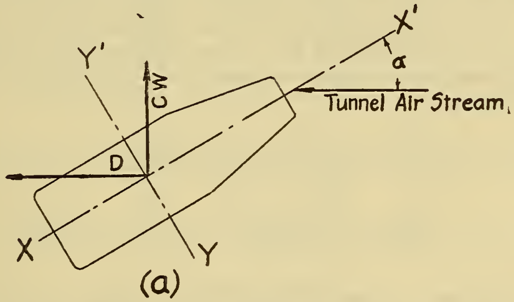
$$V_R = \sqrt{V_A{}^2 + V_W{}^2 + 2V_A . V_W \cos \beta} \qquad (1)$$

and

$$\sin \alpha = \frac{V_W \sin \beta}{V_R} \qquad (2)$$

In testing the models in the wind tunnel it was convenient to represent the relative wind vector, $V_R$, by the air stream vector. In the tests the model was turned through various angles and the deflections along the airstream and at right angles were measured. The corresponding forces (fig. 4 (*a*)), the drag, *D*, and cross wind force, *CW*, were computed from the deflections.

In reality the direction of motion of the automobile is along its longitudinal axis *X–X′* (fig. 4 (*a*)) inclined to both *D* and *CW* and it is therefore necessary to determine the force which acts along *X–X′*,



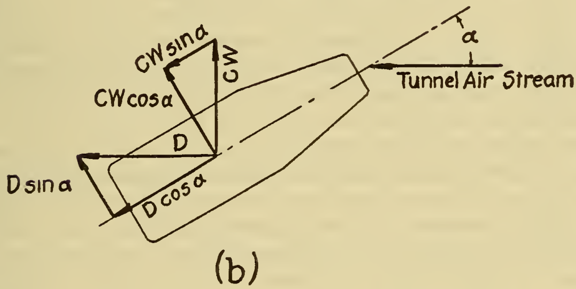




Figure 4.—*Diagrams illustrating the resolution of drag and cross wind forces on the longitudinal and lateral axes of the automobile.*

*D*=drag force. *CW*=cross wind force.

tending to retard the car directly (the longitudinal force) and the force acting at right angles to *X–X′*, tending to thrust it across the road (the lateral force). The resolution of *CW* on *X–X′* produces a part of the longitudinal force, the resolution of *D* on *X–X′*, the remainder. Likewise the resolution of *CW* on *Y–Y′* produces a part of the lateral force and a resolution of *D* on *Y–Y′* produces the remainder (fig. 4 (*b*)). The direction of the natural wind must be considered in determining the signs of its force components. If the wind is from the forward quarter as indicated in figure 3 (*b*), then

$$\text{Longitudinal force} = D \cos \alpha - CW \sin \alpha$$

and

$$\text{Lateral force} = D \sin \alpha + CW \cos \alpha$$

## V. RESULTS OF THE LONGITUDINAL AND LATERAL FORCE TESTS

Table 2 gives the longitudinal and lateral force coefficients corresponding to a range of angles of the relative wind (or yaw) of 0° to 180° for models 1 and 2 and 0° to 18° for model 3. The ratios of the longitudinal and lateral forces to the drag of the models at zero yaw are also given. It will be noted that the longitudinal force is not zero when the relative wind is at right angles to the axes of models 1 and 2, presumably due to the curvature of the bodies. The maximum ratio of lateral force to drag at zero yaw observed in the tests was 3.5 and occurred when the no. 1 sedan model was placed at right angles to the relative wind.

As an illustration of the magnitudes of the lateral and longitudinal forces, assume that the sedan represented by model 3 is moving at a speed of 50 miles per hour with a natural wind of 20 m.p.h. blowing against it at an angle of 20°, a not uncommon condition.

The composition of the vectors is accomplished by the use of formula (1) thus:

$$V_R=\sqrt{50^2+20^2+(2\times 50\times 20\times 0.94)}=69.0\text{ m.p.h.}$$

and

$$\sin\alpha=\frac{20\times 0.34}{69}=0.099;\ \alpha=5.7°$$

The relative wind, therefore, acts at an angle of 5.7° to the axis of the model with a velocity of 69.0 m.p.h. From table 2, the value for the longitudinal force coefficient for the model 3 sedan is 0.0018 (when $\alpha=5.7°$), which, assuming a maximum frontal area of 25 sq. ft., gives a longitudinal force of $0.0018\times 25\times 69^2=214$ lb. Likewise the lateral force is $0.0008\times 25\times 69^2=95$ lb.

When the wind blows from the rear quarter its effect is partly to aid the progress of the car and partly to retard it indirectly by giving rise to a side thrust, which increases the tire resistance. The magnitudes of the forces can be determined by the preceding method.

An empirical equation for the lateral force which approximately fits the data obtained using models 1 and 3, up to angles of the relative wind of 20° is:

Lateral force = 0.075 × angle of relative wind (degrees) × drag for zero angle of relative wind at the resultant air speed (not car speed).

Since a side wind increases the resultant air speed, the longitudinal force also is increased by a side wind. However, the longitudinal force coefficient varies but slightly from the drag coefficient at zero relative wind for this range of angles.

TABLE 2.—*Lateral and longitudinal force coefficients*

Longitudinal force $= D \cos \alpha - CW \sin \alpha$, lateral force $= CW \cos \alpha + D \sin \alpha$

| Angle[1] of yaw ($\alpha$) (in degrees) | Longitudinal force $\div AV^2$ | Ratio longitudinal force to drag at 0° yaw | Lateral force $\div AV^2$ | Ratio lateral force to drag at 0° yaw |
|---|---|---|---|---|
| SEDAN (MODEL 1) $K$=0.0017 | | | | |
| 0 | [2] −0.0017 | 1.0 | [2] 0.0 | 0.0 |
| 45 | −.0014 | .8 | −.0053 | 3.1 |
| 90 | −.0009 | .5 | −.0059 | 3.5 |
| 135 | +.0016 | .9 | −.0053 | 3.1 |
| 180 | +.0017 | 1.0 | 0.0 | 0.0 |
| TOURING CAR (MODEL 2) $K$=0.0019 | | | | |
| 0 | [2] −0.0019 | 1.0 | [2] −0.0002 | 0.1 |
| 15 | −.0026 | 1.4 | −.0014 | .7 |
| 30 | −.0029 | 1.5 | −.0029 | 1.5 |
| 45 | −.0025 | 1.3 | −.0038 | 2.0 |
| 90 | −.0009 | .5 | −.0049 | 2.6 |
| 135 | +.0024 | 1.3 | −.0045 | 2.4 |
| 180 | +.0018 | 1.0 | −.0004 | .2 |
| SEDAN (MODEL 3) $K$=0.0018 | | | | |
| | [2] −0.0018 | 1.00 | 0.0 | 0.0 |
| 4 | .0018 | 1.00 | [2] −.0006 | .3 |
| 8 | .0018 | 1.00 | −.0011 | .6 |
| 12 | .0018 | 1.00 | −.0016 | .9 |
| 16 | .0018 | 1.00 | −.0021 | 1.2 |
| 18 | .0019 | 1.06 | −.0023 | 1.3 |

[1] Same as angle of relative wind. [2] A minus sign indicates a retarding effect.

## VI. CONCLUSION

The values for $K$ given herein apply only to replicas of the models tested and no precise prediction can be made of the values for $K$ to be applied to body shapes greatly different from the ones tested. However, the results of the drag tests illustrate the progress in automobile streamlining during the past decade. From a comparison of the values obtained for $K$ in the Bureau of Standards tests, table 1, it is evident that while the car body of the present day represents some progress there still remains room for improvement. The value of the resistance coefficient for the present-day car (0.0014) is about 80 percent of that for the 1928 model and it appears possible to reduce this by at least one half. To reach the lower figure may, however, involve some radical changes in mechanical design.

The effect of wind from the forward quarter, often felt as a sharp deceleration while driving, is not due entirely to the longitudinal component of the wind but in part to the lateral component which gives rise to tire deformation, and consequently, increased tire resistance.

The problem of maintaining steering control when the automobile is driven in side winds of considerable velocities should be studied in detail. A knowledge of the magnitudes of the air moments acting about the center of gravity of the car in the horizontal plane is important in this connection as well as a knowledge of the lateral and longitudinal forces. A complete investigation of the aerodynamic characteristics of the automobile body also involves the determination of lift, as well as drag, and the moment about the center of gravity in the vertical plane. These forces and moments are determinable by means of models in the wind tunnel and further work along the lines indicated above is desirable.

WASHINGTON, June 6, 1933.